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Proton radiography of magnetic fields in laser produced plasmas

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Abstract: Electromagnetic fields generated by the interaction with plasmas of long-pulse laser beams relevant to inertial confinement fusion have been measured. A proton beam generated by the interaction of an ultraintense laser with a thin metallic foil is used to probe B fields. The proton beam then generated is temporally short (of the order of a ps), highly laminar and hence equivalent to a virtual point which makes it an ideal source for radiography. We have investigated, using face-on radiography, B fields due to the non colinearity of temperature and density gradients at intensity around 5×10^{13} w/cm^2.

1.Introduction

The generation of magnetic and electric fields in the laser plasma interaction is of great interest in the context of high energy density physics [1]. A detailed knowledge of the hohlraum plasma evolution is required for improving hohlraum design and for benchmarking radiation hydrodynamics codes. Megagauss B fields generated in long pulse irradiation modify the heat flow and then alter n_e and T_e distributions leading to plasma instabilities [2]. In the case of long pulse and low intensity irradiation, the main mechanism for the generation of B fields is the non-collinear density and temperature gradients ($\nabla ne\times\nabla Te$) [3,4]. The magnetic fields are then generated on the edge of the focal spot. The Faraday rotation equation combined with a simplified version of the Ohm's law can then describe the B field evolution:

$$\partial B/\partial t \approx \nabla \times (v \times B) - \frac{1}{en_e}\nabla n_e \times \nabla T_e \quad [1]$$

where v is the plasma velocity.

Previous experiments have been made to study B fields in ICF relevant plasmas. The first experiments to measure B fields in plasma used Faraday rotation of an optical probe beam [5]. This technique is limited due to the presence of the B fields close to the critical density where the optical probe beam is strongly deflected by the density gradient. Some recent experiments have used proton deflectometry [6] to measure B fields in long pulse plasmas. In the experiment discussed here, protons are emitted from the interaction of a short pulse with a thin metal foil. The proton source is then polychromatic (from a few hundred keV to about 40 MeV) [7] and emitted during ~1 ps.

2. Experimental arrangement

The experiment was carried out at the Titan laser facility. A short pulse laser beam (80J in 500 fs) is focused on a thin metallic target to a 10 micron spot leading to peak intensity around 10^{20} w/cm^2. A 50 micron tungsten foil is used to produce the proton beam. The sheath created by the hot electrons at the back of the target accelerates the protons coming from impurities at the surface of the target. At these intensities the proton spectra extends from a few keV to about 40 MeV. A long pulse beam (430J in 1 ns) is used to create the B field. The long pulse beam at λ=1064 nm is focused to a 1 mm spot with intensity around 5×10^{13} w/cm^2 on a 5 micron thin Aluminum target (figure 1).

The proton beam probes the B field in a face-on geometry. Proton deflectometry [8] is used to estimate the amplitude and the spatial distribution of the fields. A mesh (from 400 to 1000 lines per inch) is placed between the proton target and the long pulse target. The proton detector is 6 cm from the proton target; it is composed of a multilayer assembly of radiochromic film [9]. Because the ions release most of their energy at the Bragg peak, each layer of film provides a quasi-monochromatic image.

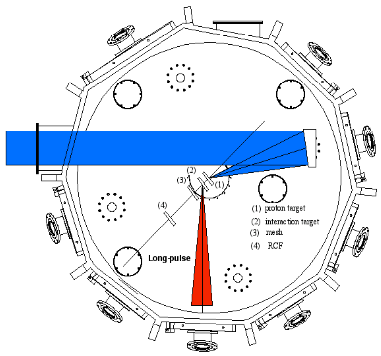
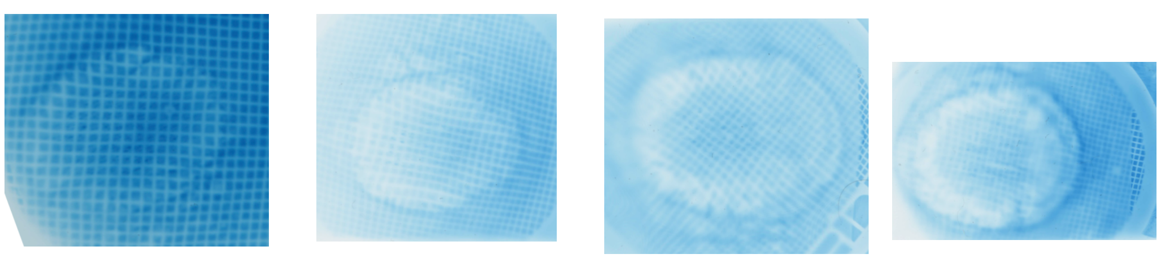


Figure 1: experimental setup of the proton deflectometry experiments

A modified Nomarsky interferometer [10] in the optical range (a few mJ in 500 fs at 532 nm) was used to provide a side-on interferogram of the long pulse plasma. This allows use to retrieve the electronic density in the long pulse plasma, and it also gives us a scaling of the plasma used in the modeling of the proton trajectory when probing the plasma.

2.Experimental results

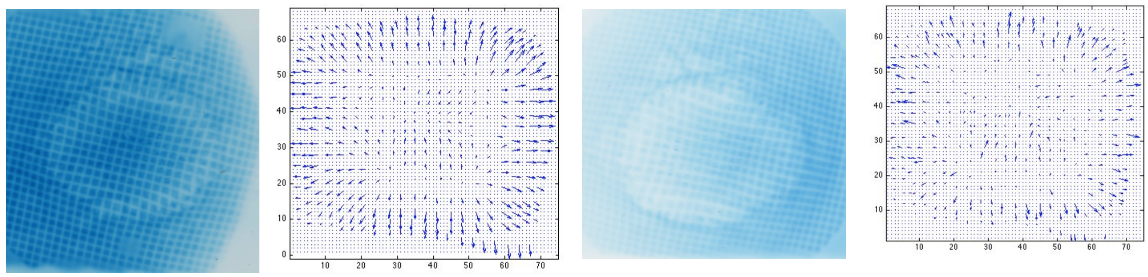
According to LASNEX [11] simulations, face-on radiography is mainly sensitive to B fields while side-on radiography is sensitive to electric fields.The B fields were then probed face-one at different time delays between the long pulse and the short pulse. Figure 2 shows the mesh deflections in the proton beam at different time delays (-100, 0, 200 and 600 ps). Special care (by tuning the laser energy and the target thickness) was taken to get initially a straight mesh that is used as a reference to estimate the mesh displacement. A proton pile-up is visible at the edge of the plasma bubble where the B fields are the stronger.At longer delays (600 ps), the proton pile-up becomes asymmetrical probably due to the presence of resistive instabilities [12].



a) b) c) d)

Figure 2: results of face-on deflectometry of 11.3 Mev protons through the long pulse plasma at different times a) -100 ps , b) 0 ps (rising edge of the long pulse), c) 200 ps and d) 600 ps

Assuming that the protons only probe B fields in the face-on geometry, the mesh distortions in the detector plane are directly related to the product B× dl where B is the amplitude of the b field and dl is the spatial scale of the B field. A routine was developed to track the mesh distortions induced by the B fields. We use the part of the image where the mesh is straight as a reference to calculate the mesh motion. Figure 3 shows for two different times (-100 ps and 0 ps) a representation of the mesh distortions. It shows that the stronger B fields are located on the edge of the focal spot since the mesh is un-deflected near its center.



a) b) c) d)

Figure 3:a) c) Deflectogram images at -100 ps and 0 ps time delay were used to deduce maps of the B field at the foil. b), d) show displacement vectors. Arrays of displacement amplitudes are shown as images c) ,d); each pixel represents one beamlet, with value proportional to displacement. The location of each beamlet can be compared with the location it would have had with no B fields (beamlets on the image edges define the grid of un-deflected locations).

3. Modelling

The deflectograms are interpreted using a routine that models the proton trajectory in the plasma. Protons are deflected by the Lorentz force. In the face-on geometry, the electric field amplitude is set to zero. A toroidal B field profile is used in the routine, the long pulse interferograms give the dimensions of the plasma expansion. The routine's parameters (distance from the proton source to the plasma and to the detector) are set to match the experimental conditions. As the plasma dimensions are set by the interferograms, we only tuned the B field amplitude to match the experimental data. The maximum value of the B field is found to be 0.6 Mgauss to match the experimental data. This value is found to be quasi-constant in time, The stronger deflections, observed at longer delay, are caused both by the longer plasma scale and by the modification in the B field curvature induced by the plasma expansion

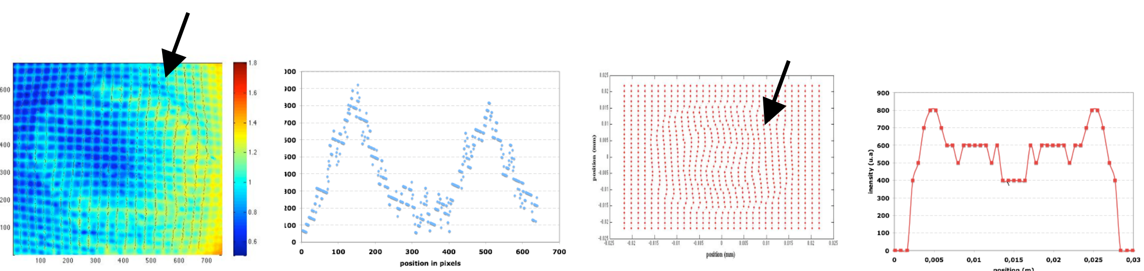


Figure 4: experimental (a) and simulated (b) deflectograms of 11.3 Mev protons. c) and d) are line-outs of the mesh displacement along a single mesh element.(marked by the back arrow). The mesh element displacement is the result of the product B× dl, where dl is the plasma expansion given by the interferogram. B is then tuned so that the simulated displacements match the experimental data. In this case, the magnitude of the magnetic field is determined to be 0.6 Mgauss.

The LASNEX simulations presented on figure 5 confirm this behavior. The maximum of the B field amplitude is located on the edge of the focal spot and its amplitude is frozen as the plasma expands. LASNEX predicts a B field amplitude of 0.45 MG while the experimental data gives 0.6 MG. This discrepancy is probably due to the non-uniformity of the 1 mm focal spot. This non-uniformity could lead to a non-symmetrical B field that explains this difference.

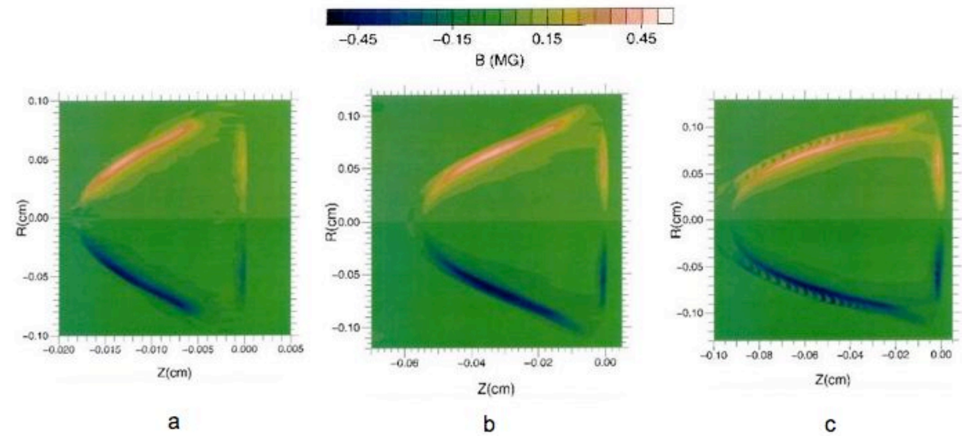


Figure 5: Time evolution of B field strength on a cross section of the plasma bubble, simulated by LASNEX for the experimental conditions of Fig. 2. In each case, the horizontal coordinate z is distance from the foil (assuming the laser is incident from the left) and the vertical coordinate R is the distance from the central axis of the plasma bubble.

4. Conclusion

Proton deflectometry has been applied to study the magnetic fields induced by the interaction of a long pulse laser with a thin metallic target. The characteristics of the laser created proton beam (short pulse duration, high energy up to 30 Mev) provide high resolution deflectograms of the magnetic field. The time evolution of the magnetic fields have been studied. At intensities around 10^{14} W/cm^2, the amplitude of the magnetic field is about 0.6 Mgauss. Those experimental results have been compared to 2D hydro simulations and are in agreement with the experimental data.

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